E3S Web of Conferences **376**, 03024 (2023) https://doi.org/10.1051/e3sconf/202337603024
ERSME-2023

Finite element simulation for microclimate normalization at the crane operator workplace

Yuriy Bulygin[1*], *Viktor* Maslensky[1], *Ekaterina* Shchekina[1], *Denis* Ashikhmin[1], *Vadim* Baranichenko[1], and *Aleksander* Pavlikov[1]

[1]Don State Technical University, 1, Gagarin square, 344003 Rostov-on-Don, Russian Federation

Abstract. The object of the study is the cabins of technological machines, where an unfavorable microclimate is observed. The method of mathematical and computer modeling used in the study is relevant and allows significantly speed up the design process due to the transition from a large number of field tests to virtual numerical experiments. The adaptation of the known mathematical models of thermal radiation and a model of a continuous medium based on the Navier-Stokes and heat transfer equations to the solution of the problem of determining the thermodynamic parameters in the cabins of technological machines has been carried out. The methodology for calculating and selecting the main equipment of the climatic system of the crane cabins has been clarified based on the developed finite element 3D models of the cabins. In addition, thermal protection equipment was used to reduce the load on the climate system. The using of modeling permit significantly speeds up the design process. Keywords: metallurgical crane, microclimate, modeling, climate system.

1 Introduction

New possibilities for solving the problem of microclimate normalization, of course, appear with the development of information and telecommunication technologies, means and methods of mathematical and computer modeling. Mathematical and computer modeling of heat and mass transfer and determination of thermodynamic parameters, mobility of air flows in the cabin of a technological machine is an important stage on the way to designing a climate system with the ability to control it depending on changing environmental parameters [1].

The purpose of this study is the developing of the mathematical models of thermal radiation, gas dynamics and heat and mass transfer, as well as finite element 3D models for the cab of a metallurgical crane.

To achieve this goal, it is necessary to solve the following **tasks:**

1. Analysis and systematization of existing methods and techniques for calculating thermal radiation when exposed to various kinds of heat sources.
2. Experimental studies and physical modeling of heat and mass transfer processes in order to check the adequacy of mathematical models.

* Corresponding author: bulyur_rostov@mail.ru

3. Adaptation of mathematical models of heat and mass transfer processes to the calculation algorithm and selection of microclimate normalization systems for the cabins of technological and mobile machines.

4. Proposal of engineering technical solutions through a rational combination of air conditioning systems and thermal protection means.

The construction of mathematical models for describing ventilation processes is based on the equations of motion, continuity of the medium, and thermal conductivity. Since the differential equations of Navier-Stokes and heat transfer do not have an analytically exact solution, it is proposed to use the finite element method for numerical solutions of model equations. Quantities such as the coefficients of turbulent viscosity, turbulent exchange and thermal conductivity are not generally known for turbulent flow. In this regard, to solve the turbulent flow equation, additional dependencies are required, obtained from various turbulence models, for example, k-epsilon, k-omega, etc. Various models of thermal radiation were analyzedsuch as Rosseland, P-1, discrete transfer, surface-to-surface (S2S) and discrete ordinates (DO). Radiation transfer and surface heating by artificial sources is well described by the discrete ordinate (DO) radiation model. It covers the entire range of optical thicknesses and allows solving problems ranging from surface radiation to penetrating radiation in combustion problems [2-4].

The finite element method is chosen for the numerical solution of equations. It is implemented in modern ANSYS software, where CFX and Fluent modules are provided for studying heat and mass transfer processes in liquids and gases. Non-gray light is simulated in ANSYS Fluent using a gray bar model.

2 Mathematical model of the thermodynamics of the crane cab (forklift)

To calculate the thermodynamic parameters of the air inside the cabins of technological machines, the discrete ordinate (DO) radiation model was adapted. The model treats the directional radiation transfer equation (RTE) as a field equation:

$$\nabla \cdot (\mathrm{I}(\vec{r},\vec{s})\vec{s}) + (a+\sigma_S)\,\mathrm{I}(\vec{r},\vec{s}) = an^2\frac{\sigma T^4}{\pi} + \frac{\sigma_S}{4\pi}\int_0^{4\pi}\mathrm{I}(\vec{r},\vec{s})\Psi\left(\vec{s}\cdot\vec{s}'\right)d\Omega', \quad (1)$$

where $\vec{r}$ is the position vector, $\vec{s}$ is the direction vector, $\vec{s}'$ is the vector of the direction of scattering, s is the path length, a is the gas absorption coefficient, n is the refractive index of the medium, σ_s is the scattering coefficient, σ is the Stefan-Boltzmann constant ($\sigma = 5{,}67 \cdot 10^{-8} \mathrm{W} \cdot \mathrm{m}^{-2} \cdot \mathrm{K}^{-4}$), I is the radiation intensity, T is the local gas temperature, Ψ is the phase function, Ω' is the solid angle, $(a + \sigma_s)$ is the optical thickness or opacity of the medium.

The total intensity $\mathrm{I}(\vec{r},\vec{s})$ in each direction $\vec{s}$ at position $\vec{r}$ is calculated as:

$$\mathrm{I}(\vec{r},\vec{s}) = \sum_k \mathrm{I}_{\lambda_k}(\vec{r},\vec{s})\Delta\lambda_k, \quad (2)$$

where the summation occurs over the wavelength ranges [2, 5, 6].

The boundary conditions for the non-gray DO model are applied on a bandwidth basis. In-strip processing is the same as for the gray DO model. The connection between energy and radiation intensities in a cell (COMET) accelerates the convergence of a finite volume scheme for radiative heat transfer. This method results in a significant improvement in convergence for conditions involving optical thicknesses greater than 10. These conditions are usually found in glass melting installations, which are close to the considered technological processes.

3 Mathematical model of thermogasdynamics for the mobile machine cab

The initial equations are the well-known system of Navier-Stokes and turbulent heat transfer equations, as well as boundary conditions. The turbulent movement of air flows inside the cabins of construction cranes was simulated using the Shear-Stress Transport (SST) k-ω turbulence model. The model is designed to effectively combine a robust and accurate near-wall k-ω model with a k-ε free flow far-field model.

The SST k-ω model has a structure similar to the standard k-ω model:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left(\widetilde{G}_k\frac{\partial k}{\partial x_j}\right)+G_k-Y_k+S_k \quad (3)$$

$$\frac{\partial}{\partial t}(\rho\omega)+\frac{\partial}{\partial x_j}\left(\rho\omega u_j\right)=\frac{\partial}{\partial x_j}\left(\widetilde{G}_\omega\frac{\partial\omega}{\partial x_j}\right)+G_\omega-Y_\omega+D_\omega+S_\omega. \quad (4)$$

In equations (3) and (4), G_k is the production of kinetic energy of turbulence and is determined in the same way as in the standard k-ε model, G_ω is the generation of ω, which can be calculated in the same way as in the standard k-ω model. $\widetilde{G}_k$ and $\widetilde{G}_\omega$ are the effective diffusion capacity k and ω, Y_k and Y_ω are the dissipation capacity k and ω due to turbulence, D_ω is the cross-diffusion condition, S_k and S_ω are the determined initial conditions. Turbulent heat transfer can be modeled using the concept of Reynolds analogy with turbulent momentum transfer [7-11].

4 Constructions of three-dimensional models of cabins

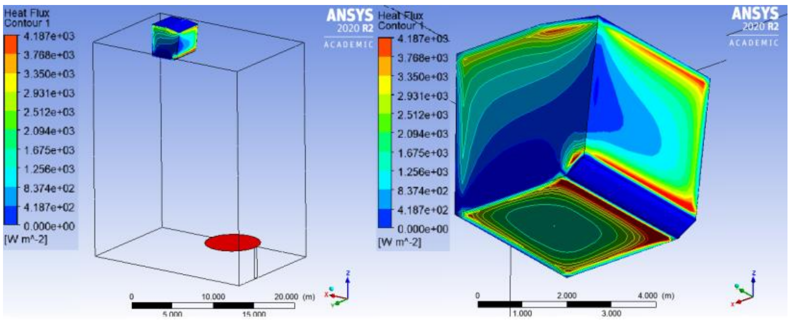
Three-dimensional 3D models of the cabins of the metallurgical crane and the UAL forklift truck and the sources of thermal radiation affecting them of the DSP (arc furnace) section of the electric steel plant of Pjsc Tagmet were created.

First, the heat flow on the surfaces of the cab was calculated, and then the parameters of the microclimate in its internal volume, where the operator's workplace is located, were determined. The boundary conditions of the models of thermal exposure were set by the temperatures of the sources. The sizes of radiation sources and objects of irradiation and their relative position were taken into account. The calculated heat fluxes on the outer surfaces of the walls, the ambient air temperature and the heat transfer coefficients were set when calculating the temperature fields inside the cabins of technological machines as boundary conditions. Since a large gradient of fields is assumed in the region of the walls, the construction of wall layers was a mandatory requirement. The computational mesh of finite elements was represented by cells in the form of tetrahedrons. The problem was solved in a static setting. The outside air temperature was set equal to 45 °C. Solar radiation was received in the form of a heat flux from the sun (800 W/m^2) directed at an angle of 45 °C to the cab [3, 12-14].

5 The results of calculating thermal radiation, temperatures on the surfaces of walls and in the internal volume of the cabins of technological machines

The calculations were carried out for a metallurgical crane and a forklift with different options for the operation of heat sources. Figure 1 shows the walls of the cabin facing the furnace; you can observe the maximum heat fluxes occurring on the floor of the crane cabin.

In the case when, according to the conditions of the technological process, the roof of the DSP-150 furnace is closed, the values of heat radiation from the walls of the crane cabin are significantly reduced. Also, the temperature fields were calculated near the railings of the cabins of the metallurgical crane (Fig. 2a) and the auto-loader (Fig. 2b). The air temperatures near the outer surfaces, which were 36.5 °C for a metallurgical crane and 54.4 °C for a forklift, in turn, are the boundary conditions for further calculation of the air temperature in the interior of the cabins. The calculation results show that the walls of the cabs facing the heat sources are exposed to the maximum heat radiation, it is the floor, front and right for a metallurgical crane and front and top for a forklift. In this case, the maximum relative error of the engineering method of calculation in comparison with modeling is 34 % [12, 15, 16].

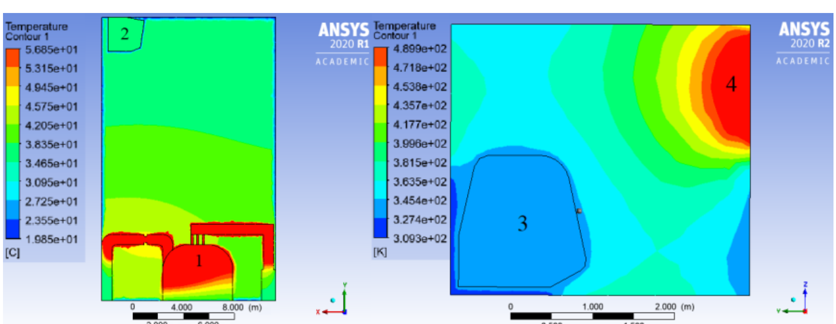


a b

Fig. 1. Radiation source (DSP-150) with an open roof of the furnace (a) and irradiated surfaces of the cab of the metallurgical crane (b).

The amount of irradiation of the outer surfaces of the crane cabin exceeds the sanitary and hygienic standard by 6.1-12.0 times, for a forklift the excess is 20.9-30.3 times. In the internal volume of the cabins of technological machines, the air temperature is 42.8 °C and 51.2 °C for a metallurgical crane and a forklift, respectively, which significantly exceeds the sanitary and hygienic standard.

Comparison of the experimentally obtained temperatures of the equipment surfaces in the DSP (arc furnace) section (obtained by the factory laboratory within the framework of Special Assessment of Working Conditions) and the temperatures calculated in ANSYS FluidFlow (CFX) showes that the values of the relative error did not exceed 5 % [15, 17, 18].



a) b)

Fig. 2. Temperature fields near the fences of the cabins of the metallurgical crane and the auto-loader: 1 is DSP-150, 2 is a cabin, 3 is a cabin, 4 is the flame reflective furnace.

6 Discussions and suggestions

On the basis of the developed finite element 3D models of the cabins, the methodology for calculating and selecting the main equipment for the climatic system of the crane cabins was refined. Thermal protection elements were also calculated to reduce the load on the climate system. At the same time, when using the method of thermal irradiation diagrams, a decrease in the heat flux by a heat-reflecting screen or double glazing is calculated taking into account the reduced emissivity. The results of evaluating the effectiveness of the elements of thermal protection of the cab of a metallurgical crane are shown in Fig. 3.

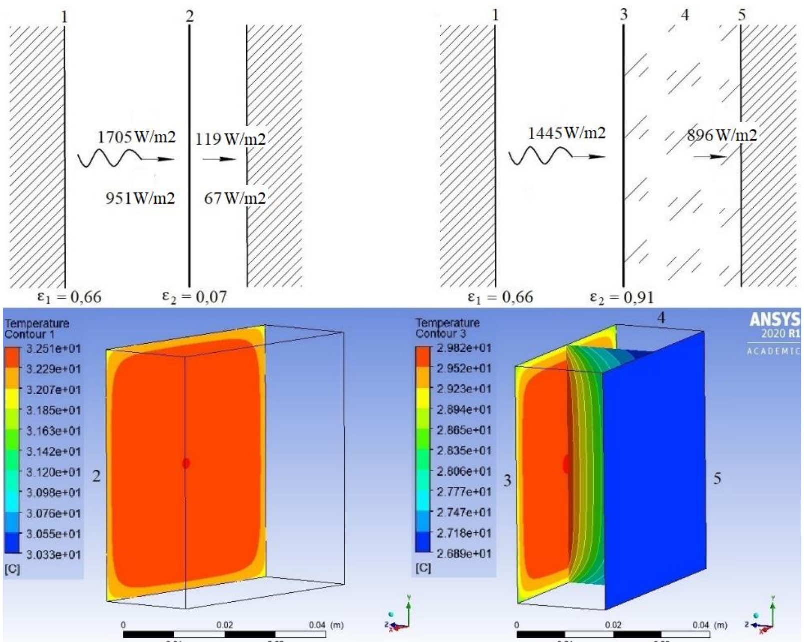


Fig. 3. Reduction of thermal radiation and temperature: a with the heat-reflecting screen, b with the double glazing with an air gap. 1 is the radiation source, 2 is the screen, 3, 5 are the first and second row of glasses, 4 is air gap.

Thus, an aluminium screen with a thickness of 0.003 m, installed on the outer surface of the floor and the right wall of the metallurgical crane cabin, will reduce the level of thermal radiation to 119 and 67 W/m^2, respectively (14.3 times) due to the low emissivity of aluminium (ε = 0.07). At the same time, the temperature behind the screen will reach 32.4 °C, which is 4.1 °C lower than the temperature of the outer surface of the floor and the right wall of the cab before the installation of the heat-reflecting screen. After replacing the front single glazing with a double one, with a thickness of each glass of 0.003 m, with an air gap of 0.02 m thick, the heat irradiance decreased slightly (1.6 times) and amounted to 896 W/m^2.On the other hand, due to the low thermal conductivity of glass and air, the temperature on the surface of the second row of glasses can be reduced by 9.5 °C. As a result, after the introduction of thermal protection elements, the heat flow through the enclosing surfaces of the metallurgical crane cabin will decrease by 1.6 times. The heat gain from heat sources in the steel-making shop will decrease by 2.1 times. This will eliminate undue stress on the projected climate system. Thus, the total heat input into the cab of the metallurgical crane will be 3229 W [12, 19, 20].

7 Conclusion

1. The presented model of thermal radiation takes into account, along with the geometry of the cabin and radiation sources, heat exchange by radiation, as well as heat transfer to air by convection and thermal conductivity.
2. The model of a continuous medium, based on the Navier-Stokes and heat transfer equations, uses turbulence models, boundary conditions set explicitly by heat transfer coefficients, external temperature and solar radiation.
3. Finite element 3D models have been developed, using the example of the cab of a metallurgical crane and a forklift.
4. The methodology for the selection of equipment for the climatic system, adapted to the technical characteristics of the equipment of the suppliers and the conditions of the protocol tests carried out by them, is proposed.

References

1. R.V. Zhokhov, A.A. Korotkiy, Safety of technogenic and natural systems **3**, 2-5 (2019) https://doi.org/10.23947/2541-9129-2019-3-2-5
2. F.M. Nia, S.A.G. Nassab, A.B. Ansari, J. Therm, Sci. **128**, 94–104 (2018) https://doi.org/10.1016/j.ijthermalsci.2018.01.021
3. F.M. Nia, S.A.G. Nassab, J. Nonlin, Sci. Num. **18(1)**, 29–39 (2017) https://doi.org/10.1515/ijnsns-2015-0134
4. M. Atashafrooz, S.A. Nassab, G.J. Mech, Sci. Technol. **26(10)**, 3357–3368 (2012) https://doi.org/10.1007/s12206-012-0804-x
5. F. Chabane, M. Noureddine, A. Brima, J. Heat, Tech. **36(3)**, 855–860 (2018) https://doi.org/10.18280/ijht.360311
6. N.S. Park, S.C. Ko, J. Mech, Sci Technol **25**, 713-719 (2011) https://doi.org/10.1007/s12206-011-0106-8
7. Y.I. Bulygin, E.V. Shchekina, V.V. Maslensky, D.S. Popov, A.V. Tryukhan, AIP Conference Proceedings **2188**, 050033 (2019) https://doi.org/10.1063/1.5138460
8. F.R. Menter, R. Lechner, A. Matyushenko, Notes on Numerical Fluid Mechanics **142**, 101-109 (2020) https://doi.org/10.1007/978-3-030-25253-3_10
9. F.R. Menter, International Journal of Computational Fluid Dynamics **23(4)**, 305-316 https://doi.org/10.1080/10618560902773387
10. P.E. Smirnov, F.R. Menter, Journal of Turbomachinery **4**, 1-8 (2009) https://doi.org/10.1115/1.3070573
11. K.V. Deshmukh, M.F. Modest, D.C. Haworth, Computational Thermal Sciences **2**, 207-230 (2009) https://doi.org/10.1615/ComputThermalScien.v1.i2.60
12. B.Ch. Meskhi, Yu.I. Bulygin E.V. Shchekina, A.V. Medvedev, Occupational Safety in Industry **12**, 16-22 (2018) https://doi.org/10.24000/0409-2961-2018-12-16-22
13. S.A. Borozdin E.V. Neskoromnyi S.A. Maiatskii, Vestnik USATU **1**, 31-39 (2022) https://doi.org/10.54708/19926502_2022_2619531
14. J. Cai, R. Marquez, M.F. Modest, Journal of Heat Transfer **11**, 112702 (2014) https://doi.org/10.1115/1.4026169
15. V.V. Maslensky, Yu.I. Bulygin, Safety of technogenic and natural systems **1**, 10-20 (2021) https://doi.org/10.23947/2541-9129-2021-1-10-20

16. N.A. Tseligorov, A.K. Naser, A.I. Ozerskiy, E.N. Tseligorova, IOP Conference Series: Earth and Environmental Science **723**, 052020 (2021) https://doi.org/10.1088/1755-1315/723/5/052020
17. B. Meskhi, Y. Bulygin, E. Shchekina, V. Maslensky, IOP Conference Series: Earth and Environmental Science **403**, 012089 (2019) https://doi.org/10.1088/1755-1315/403/1/012089
18. L.V. Borukhova, A.S. Shebeko, Energetika. Proceedings of CIS higher education institutions and power engineering associations **1**, 65-78 (2016) https://doi.org/10.21122/1029-7448-2016-59-1-65-78
19. B.Ch. Meskhi, Yu.I. Bulygin, V.V. Maslensky, I.N. Loskutnikova, Occupational Safety in Industry **2**, 7-14 (2021) https://doi.org/10.24000/0409-2961-2021-2-7-14
20. Yu. Babenkov, A. Ozersky, V. Romanov, G. Galka, M. Morozov, E3S Web of Conferences **273**, 07001 (2021) https://doi.org/10.1051/e3sconf/202127307001.